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Policy implications for improved cook stove programs—A case study of the importance of village fuel use variations

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HIGHLIGHTS

- Household data from six different villages were used to calculate potential benefits from an improved stove program.
- The possible monetary savings and reductions in CO_2 equivalent emissions were calculated.
- The results show benefits as non-linear functions of stove improvements.
- The results show large variations among villages in the functions mapping stove improvements to benefits.

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ABSTRACT

Despite the long history of cook stove programs, very few have been successful, often only in areas where biomass is purchased or there is a biomass shortage. Several studies have described how rural households generally rely on several different fuels; which fuels are used may depend on various household characteristics such as location and income. This article explores possible consequences of variations in fuel usage for improved cook stove programs and how this may vary between different areas. Reductions of CO_2 equivalent emissions and monetary savings are calculated for hypothetical cook stove deployment using data from a rural energy survey in the Vĩnh Phúc province of northern Vietnam. The results indicate that the areas may respond differently to the various stove options, both in terms of economy and emission reductions. Furthermore, there are large differences in emission reduction calculations when only Kyoto-gases are included and when non-Kyoto greenhouse agents are added. Assumptions regarding household behavior and stove efficiencies have large impacts on the results, indicating a need for further research on how improved cook stoves may influence households' fuel choices.

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1. Introduction

Rural households in the developing world rely heavily on solid biomass as a means for cooking (Foell et al., 2011). Inefficient stoves with incomplete combustion lead to emissions that pose severe health risks (Bruce et al., 2000; Torres-Duque et al., 2008). Furthermore, the incomplete combustion also leads to the formation of black carbon, a very potent greenhouse agent (Bond and Sun, 2005; Bond et al., 2011; Hansen et al., 2007; Ramanathan and Carmichael, 2008).

Improved cook stoves (ICSs), i.e. stoves with higher efficiency and cleaner combustion, provide a possibility both for improving health and reducing greenhouse gas emissions (Grieshop et al., 2011). Initially, many stove programs were aimed at combating deforestation. The link between fuel wood collection and deforestation has been questioned by some (Arnold et al., 2006; Dewees, 1989) and certainly varies strongly between areas. Furthermore, in areas where charcoal use is common, a more efficient utilization may substantially reduce deforestation, especially around urban centers (Bensch and Peters, 2012a). The dissemination of improved cook stoves often also aims at reduction of the time spent on fuel wood collection and on meal preparation. However, since fuel wood collection and cooking are often performed by women while financial decisions are often handled by the male head of household, this investment may not be prioritized. See for example Miller and Mobarak (2013) for a discussion on how such divisions of roles within households may lead to suboptimal decisions in relation to improved cook stoves.

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Furthermore, the time spent on fuel wood collection may not be perceived as an issue due to social patterns (Pachauri and Spreng, 2012). The main motive behind many stove programs is to decrease indoor air pollution, which, due to the combustion of solid fuels, leads to an estimated two million deaths each year, and children under the age of five and women responsible for cooking are the groups most affected (Martin et al., 2011; WHO, 2013).

Poor households in developing countries without possibilities of obtaining fuel through collection often have to spend a substantial amount of an already constrained household budget on fuel wood and the enabling of a more efficient fuel use may thus be an important strategy in poverty alleviation (Bensch and Peters, 2012b). There is also a substantial body of research linking the inefficient combustion of biomass to climate change, both directly through the production of black carbon and methane (Bond et al., 2011; Grieshop et al., 2011), and indirectly through deforestation in areas where such a link can be established. A possibility of funding stove programs through carbon credits may thus be possible. So far, programs that have received funding from the CDM mechanism have been awarded support mainly based on anticipated reduced deforestation, i.e. CO_2-emissions from biomass; black carbon is currently not included in any climate agreements.

Despite many apparent benefits from a switch to improved cook stoves, many stove programs have had a low rate of success (Bailis et al., 2009). One of the few successful examples of large scale dissemination was the Chinese National Improved Stove Program, which managed to reach a majority of rural households and a market has been sustained where households themselves are buying spare parts and new stoves (Barnes et al., 1994; Sinton et al., 2004). A factor that the Chinese stove program shares with other successful, although smaller, programs is the choice of initial intervention areas. These were chosen on the basis of biomass shortages, but also taking into account financial possibilities of the households in the area; the households were expected to purchase the stoves themselves (Smith et al., 1993). Households are generally more willing to adopt the new technology if they are purchasing the biomass and hence there are economic savings to be made from using a more efficient technology or if there is a fuel shortage in the area, typically urban or periurban areas (Barnes et al., 1994). The Chinese program also initially targeted middle income households (Smith et al., 1993).

In Africa, urban and periurban households and households with relatively higher income have also been found to be more likely to switch to an improved cook stove (Barnes et al., 1994), and the same has also been noted by companies manufacturing and selling stoves in India, where higher income households are more likely to buy them. This may be explained by the fact that these households are more likely to be able to afford an improved stove but also since these households are more likely to buy wood than to collect it, giving them a stronger economic incentive to purchase and use the stove (Shrimali et al., 2011).

Another example of a successful large scale implementation of improved cook stoves is the Jiko charcoal stove in Kenya. The Jiko program has similarities with the Chinese case, where an initially subsidized operation was commercialized. The success of the Jiko can largely be attributed to the fact that charcoal is mostly used in urban areas where households are already used for purchasing stoves and fuels (Bailis et al., 2009). Hence, the successful programs have often been where households are either forced by policies and/or fuel shortages or the households get economic benefits from switching stoves. Stove programs that have been successful due to high economic benefits have in general been located in urban areas where fuel collection possibilities are limited. Findings have suggested that many of the early stove programs failed because they tended to focus on rural areas instead of urban, and could therefore save only time and biomass but not money (Shepherd, 1990). However, even in what is considered rural areas, fuel collection may be limited and fuels are purchased to some degree (Kaul and Liu, 1992). A household that has to purchase fuels only part of the year may still save a significant amount of money by adopting a more efficient stove. Examples of more recent attempts aimed at improved charcoal stoves in urban areas have also been successful (Bensch and Peters, 2012a).

Governments and organizations can play a vital role in stove programs, as is evident from the Chinese ICS and Jiko stove disseminations, both through subsidizing stoves directly or enabling purchase through microfinance, but also through information campaigns and training local ICS startup manufacturers and repairers (Bailis et al., 2009; Smith et al., 1993). Furthermore, without an external quality control of stoves it may be difficult for households to evaluate their purchases and they may end up with underperforming stoves which in turn may lower the general interest in ICSs, which was observed when external funding withdrew from the Jiko program (Bailis et al., 2009).

There are examples where a large portion of households have used free or subsidized stoves (Bensch and Peters, 2012b; Troncoso et al., 2011). However other studies suggest that with a limited lifetime of the stoves, a functioning market where households continue to repair or renew their stoves is necessary for a sustained usage of ICSs after an initial program has ended. This is underlined in a long term study by Hanna et al. (2012), who followed household during four years in a randomized study. They found a decline in stove performance after the first year, partly due to low maintenance and a decline in usage. Even if the design is sufficiently good to make the household use the stove, if the financial means and incentives to repair or buy a new stove is lacking, the stove program may have to continue handing out stoves and parts to sustain usage. An underlying assumption of many stove programs is that time saved from fuel collection and health improvements will also have positive effects on the local economy and, thus, in the end give sufficient incentives and means for households to continue to purchase, repair and use the stoves after the initial program has ended. However, this transition will take time (WorldBank, 2011) and initial adoption and sustained usage are two different things which are pointed out by Hanna et al. (2012).

A randomized test of stove adoption was recently carried out in Senegal. Despite the fact that stoves were handed out for free in an area where most households rely on collected fuel, an almost 100% adoption of the ICS among the randomly selected households was observed (Bensch and Peters, 2012b). In addition, a 30% average decline of used fuel wood was reported with significant improvements of health indicators. The reduction in time used for wood collection was however statistically insignificant despite most households relying solely on collected fuels. Bensch and Peters (2012b) explain the lack of significance with the noisiness of the time variable due to differences in fuel collecting habits. While these results seem to contradict many of the other results and point towards a totally subsidized ICS dissemination, it should be pointed out that the area studied in Senegal is arid and under ongoing deforestation and fuel wood collection is reported to become increasingly difficult (Bensch and Peters, 2012b).

Several studies have pointed to the multiple fuel or fuel stacking strategies of rural households, e.g. Heltberg (2005), Masera et al. (2000), Peng et al. (2010), and Vahlne and Ahlgren (submitted for publication), of which the last found strong variations in village level concerning which fuels households include in their fuel mix. Indications that much of these variations could be explained by village location and household density were also found (Vahlne and Ahlgren, submitted for publication) while Peng et al. (2010) found differences between areas with different environments. Based on a statistical model describing households' fuel use together with a mapping of possible village responses to ICS dissemination, the type of ICS dissemination program needed and the potential level of success and benefits of such a program would thus be possible to predict.

The aim of this article is to explore possible impacts of village fuel mix characteristics on deployment of improved cook stoves and if these ought to have implications for stove designs and for carbon financing possibilities. Whereas several cost benefit analyses have been performed for the case of improved cook stoves they often assume that households use only one fuel.

2. Methods

Data on households' fuel usage, collected in six communes in the Vĩnh Phúc province of northern Vietnam, are used to compute monetary savings and reductions of CO_2 equivalent emissions in different areas for various assumptions on stove performance. Since improved cook stoves come in many varieties (MacCarty et al., 2008), to encompass differences between stove options, assumed efficiencies and emissions are allowed to vary between high end and low end stove options. Furthermore, the possible effects of how households may alter their fuel mixes after obtaining an improved cook stove are also explored.

This section contains first a note on the case selection and data collection; thereafter the assumptions regarding the characteristics of improved cook stoves are presented and justified, followed by a discussion regarding assumptions on how households may alter their fuel mixes. The section ends with a presentation of the calculations of emission reductions and monetary savings.

2.1. Case selection and survey

The influence of location on fuel use has been shown in several studies (van der Kroon et al., 2013). For example, Peng et al. (2010) find differences between areas with different environments. Thus, a point of departure for this study was to select villages situated in the same province but with differences with regard to the natural conditions. As indicators of the major different environments in northern Vietnam, communes in the delta, hills and mountainous areas were selected. The Vĩnh Phúc province in the North West part of the Red River delta was chosen for the study because it encompasses these three distinctive environments that are present in much of northern Vietnam, although other provinces also have this characteristic. Vĩnh Phúc covers 1371 km^2 in total divided over 152 communes of which the mountain, hill and delta regions constitute 562 km^2 (43 communes), 249 km^2 (33 communes) and 468 km^2 (76 communes), respectively (VPP, 2010).

The survey was designed in cooperation with the Institute of Energy in Hanoi, and carried out by the Institute and Vietnam Women's Union. 40 households were asked to answer a questionnaire in each commune, in totally 240 households. The questionnaire covered households' basic socio-economic status such as income, education and size, agricultural practices together with current energy use for cooking, space heating, water heating and electrical appliances. The households were asked which fuels they used for cooking and these were recorded as main, secondary and tertiary fuels. The households were also asked to estimate the share that the different fuels occupied in the households' cooking on an annual basis. From these two questions it is possible to estimate the share different fuels occupy in a household's fuel mix for cooking. Furthermore, questions were asked regarding the amount of main fuels that was used.

The units of data collection are on the commune level and these are used as the initial units of analysis. However, a useful approach may be to look at the data from different points of views and one way of adding insights is to group the data into further groups beyond the initial data collections (Bourgeois and Eisenhardt, 1988; Eisenhardt, 1989; Yin, 2009). Thus, for further comparison between groups, the initial units of analysis are grouped into larger units based on environment, i.e. mountains, hills or delta but also based on the means of commune land holdings. The last grouping may be seen as a measurement of more or less rural. It is also possible to consider the individual households themselves as the unit of analysis. To further underline and test the results of the initial grouping of communes, new inter-commune groups of households are also constructed and analyzed. Based on previous theory and results regarding rural fuel choices, e.g. the energy ladder (van der Kroon et al., 2013), households are divided based on income and the individual households land holdings.

Table 1
Emissions from considered stove options calculated from values compiled by Grieshop et al. (2011).

	Stove	kg CO_2eq/kg fuel[a]			Laboratory efficiencies[b] η
		Fuel	Total	Included in the Kyoto protocol	
Current	Tripod	Wood	1.45	0.32	0.18
	Coal stove	Coal	5.34	3.51	0.14
	LPG stove	LPG	3.33	3.11	0.54
ICS	Fan	Wood	0.18	0.01	0.40
	Chinese ICS	Wood	1.08	0.23	0.24

[a] The CO_2 emitted from biomass is assumed carbon neutral and is thus not included in the calculations. All emitted black carbon is assumed to reach atmosphere. Included emissions are CO_2 from fossil sources and methane, which are a part of the Kyoto Protocol, and black carbon, organic carbon (negative), CO, and NMHCs, which are currently not included in the Kyoto Protocol. The total kg CO_2eq/kg is calculated as the sum of the separate emissions given as kg C/kg fuel from Grieshop et al. (2011) as $\text{kg}\,CO_2\text{eq}/\text{kg}_{fuel} = \sum_i GWP_i(\text{kg}\,w/\text{kg}\,C)_i(\text{kg}\,C/\text{kg}_{fuel})_i$, where GWP_i is the GWP value for emission i, $(w/C)_i$ is the total molecular weight related to the weight of carbon atoms in the molecule and $(\text{kg}\,C/\text{kg}_{fuel})_i$ is the kg of carbon ending up in emission i. GWP-values for black carbon and organic carbon are assumed to be 455 and -35 GWP_{100} respectively (Reynolds and Kandlikar, 2008), although note that this is in the lower range of current estimations (Bond et al., 2011). Also, because of the short life span of black carbon, using, for example, GWP_{20} would yield a much higher value.

[b] As measured in the water boiling test (Grieshop et al., 2011).

2.2. Assumptions regarding improved cook stoves

There exists a large variety of improved cook stoves (Grieshop et al., 2011; MacCarty et al., 2008). One of the most efficient ICSs, which also has low emissions, is the fan powered gasifier stove (Jetter and Kariher, 2009), where an electric fan is used to control air inflow. This represents a substantial increase in both efficiency and emission reductions from previous generation ICSs and simpler, locally manufactured alternatives. To estimate an interval of emission reductions we perform calculations for both the modern gasifier stove and a representation of a more simple version, a brick stove used in the Chinese dissemination program (Zhang et al., 2000). The choice of the Chinese stove is not for representing a likely technology for future intervention, but rather for representing a lower end technology option in terms of emissions. There has not been any large scale dissemination of ICSs in Vietnam, except for the biogas program funded by the Dutch development organization SNV, primarily aimed at households with a large number of livestock. However, programs in cooperation with Vietnam Women's Union in northern Vietnam have distributed around 30,000 stoves, and many of them with a design reminiscent of the Chinese ICS (GACC, 2012; Khoi, 2009). Note that while the efficiency is allowed to vary in the calculations, the emissions per kg of biomass fuel are based on either one of the two technology options. The choice of the Chinese ICS over current low end stoves disseminated in the area is primarily motivated by the availability of emission data (Grieshop et al., 2011).

Table 1 presents figures calculated from values compiled by Grieshop et al. (2011). The top three stoves represent technologies already used in the studied area and the bottom two stoves represent a high and a low end ICS option.

In order to represent both the current and possible future support from carbon credits, we present results for total GWP emissions and for only those gases included in the Kyoto-protocol.

The efficiencies given in Table 1 are 18%, 24% and 40% for the tripod, Chinese ICS and fan powered gasifier biomass stoves, respectively. Hence switching from a tripod to a Chinese ICS would reduce needed fuel wood to 25%, while the fan powered stove would decrease fuel usage to 55% on a per meal basis. However, these values are from ideal laboratory settings, i.e. water boiling tests and are subject to uncertainties when actually used in households.

It is clear that there are some discrepancies between the efficiencies for stove options as measured in laboratory settings compared to the efficiencies obtained for usage in households. Furthermore, the difference in efficiencies may vary between cooking options. For example, applying the laboratory measured efficiency for the LPG stove to the household data and comparing with the amount of wood used for the same amount of cooking (Vahlne and Ahlgren, submitted for publication) give efficiencies below 0.1 for the tripod style cooking. To both encompass possible differences between laboratory tests and also describe a broad range of stove options, the emissions and monetary savings are calculated for stoves with an assumed reduction in needed fuel wood, on a per meal basis, for a range of 10–80%. The level of reduced need for fuel wood is henceforth labeled R.

While a more efficient stove may not necessarily produce less total GHG emissions (MacCarty et al., 2008), we use the Chinese ICS and the gasifier stove as upper and lower limits of the emissions per kg of used fuel wood and then alter the amount of needed fuel wood. As a further assumption, due to the unavailability of emission data, we assume the same emissions for agricultural residues as for purchased and collected fuel wood. The emissions may also vary due to different operations of the stoves (Huboyo et al., 2013). However due to available data it is here assumed that the stoves are operated in a similar way as in the laboratory settings, including fuel quality and moisture level (Grieshop et al., 2011; Jetter and Kariher, 2009).

The payback time as a function of the reduction in needed fuel wood is also calculated. A linear relationship between R and the cost of stove is assumed. Here, the assumption is 100,000 VND (around 5$) per 10% reduction in needed fuel wood time. The payback time, in years, is then just calculated as stove cost divided by annual monetary savings. Note that the assumption of a linear relationship does not necessarily reflect real circumstances and is chosen mainly for illustrative purposes in describing differences among villages.

2.3. Assumptions of post-ICS adoption fuel stacks

The multiple fuel (fuel stacking) strategies of rural households as described by Heltberg (2005) and Masera et al. (2000) may be due to limited access to collectable fuels at low opportunity cost, economical limits and limits in supply of commercial fuels. However, both Masera et al. (2000) and Heltberg (2005) stress that different fuels and stoves may serve different purposes best; hence having the means to use LPG for all purposes may not necessarily mean that a household chooses to do so. The possible effects of different assumptions on how households may alter their fuel mixes in response to obtaining an improved cook stove, henceforth called PIFS, post-ICS-adoption fuel stacks, depending on initial fuel mix are therefore explored in this paper.

There is research indicating that households often do not, at least in the short term, abandon their traditional fuels and cooking technologies. Zamora (2010), cited by Ruiz-Mercado et al. (2011), presents results regarding how households in two Mexican villages altered their fuel mixes after ICS adoption. Before ICS adoption, households used either only a three stone fire or a combination of LPG and a three stone fire. Few households abandoned the three stone fire completely while some households abandoned or decreased their LPG usage. The results depended on the type of cooking that was performed and cannot be directly generalized to other regions. The modern gasifier ICS is often marketed as a cheaper alternative to LPG which provides a similar cooking experience (Shrimali et al., 2011). Given a sufficiently good stove design and potential monetary savings some households may thus abandon LPG in favor of biomass. Coal may be also displaced since coal is often used as an affordable complement when collectable resources are scarce (Kaul and Liu, 1992) and because it is often a cheaper alternative to commercial fuel wood.

The survey used as a basis for this paper collected data regarding all the different fuels the households use for cooking, see Section 2.1. The survey results include the shares of the yearly cooking conducted with different fuels. However it is not clear how these fuel shares are preserved should the household obtain a

Table 2
Algorithm for calculating new fuel shares based on more efficient utilization of collected biomass; η_1 and η_2 are the efficiencies of cooking with biomass before and after ICS adoption, respectively; S_X and S_XP_X are the shares of different fuels before and after ICS adoption, respectively, A_X is the amount of a fuel needed, and C_X is the price of the different fuels per kg.

	Present	PIF1	PIF2
Agricultural residues	S_1	$S_{1PIF1}=S_1$	$S_{1PIF2}=S_1\,(\eta_2/\eta_1)$
Collected wood	S_2	$S_{2PIF1}=S_2$	If $S_{1PIF2}+S_2(\eta_2/\eta_1)<1$: $S_{2PIF2}=S_2\,(\eta_2/\eta_1)$ else: $S_{2PIF2}=1-S_{1PIF2}$
Bought wood	S_3	$S_{3PIF1}=S_3$	$S_{3PIF2}=(S_3/(S_3+S_4+S_5))(1-S_{1PIF2}-S_{2PIF2})$
Coal	S_4	$S_{4PIF1}=S_4$	$S_{4PIF2}=(S_4/(S_3+S_4+S_5))(1-S_{1PIF2}-S_{2PIF2})$ If $(1-R)A_{Wood}C_{Wood}<A_{Coal}C_{Coal}$: $\{S_{3PIF2}=S_{3PIF2}+S_{4PIF2},\ S_{4PIF2}=0\}$
LPG	S_5	$S_{5PIF1}=S_5$	$S_{5PIF2}=(S_5/(S_3+S_4+S_5))(1-S_{1PIF2}-S_{2PIF2})$ If $(1-R)A_{Wood}C_{Wood}<A_{LPG}C_{LPG}$: $\{S_{3PIF2}=S_{3PIF2}+S_{5PIF2},\ S_{5PIF2}=0\}$

more efficient way to cook with biomass. To encompass uncertainties, the calculations are performed for two different assumptions of households' PIFS. Under the first assumption, PIF1, we assume that the household's fuel mix is unaltered after the purchase of an ICS, e.g. a household using coal for half of the cooking and biomass for the remaining part is assumed to do so after receiving the ICS, but with an increased efficiency for the cooking done with biomass. Similarly, shares of biomass from different sources are assumed to be maintained.

In the second assumption, PIF2, we assume the households to act more economically if the ICS enables them to do so since an increased efficiency implies that the total amount of required fuels decreases and, thus, biomass fuels can displace other fuels. The collected fuels, agricultural residues and collected fuel wood are assumed to displace commercial fuels in proportion to the reduced need of biomass for cooking on a per meal basis. If the share of collected fuels is less than 100%, we assume that households substitute the possibly remaining coal and LPG with bought fuel wood if this option becomes more economical due to a more efficient utilization of the purchased fuel wood; otherwise, the purchased fuel wood, coal and LPG keep their respective shares of the commercial fuels (which may still decrease based on a more efficient use of collected fuels). Note that households are not assumed to switch to a more economical alternative if it is not induced by the ICS, e.g. not switch to coal since this is likely not a decision taken because of the adoption of an improved biomass stove. The algorithm for calculating the PIFS is summarized in Table 2.

In both PIF1 and PIF2 we assume that households collect fuel wood and agricultural residues only for domestic use, i.e. households are not assumed to sell fuel to any market or give to other households as a result of improved efficiency.

The different assumptions concerning PIFS can be interpreted as an attempt to capture the robustness of the possible benefits of an ICS dissemination. However, it may also be possible that the PIF resembling reality the most depends on stove design, i.e. a stove with better design might cause real PIFS to resemble PIF2 more.

It should also be noted that although PIF1 is considered here as the lower level in terms of fuel displacement, i.e. no fuel displacement, it need not necessarily be the lower limit for possible monetary savings and emissions. Stoves might not be used properly or used only sometime. For example Ruiz-Mercado et al. (2011) and Zamora (2010) found that several households that were long term ICS users did not use the ICS for all types of cooking with biomass. Bensch and Peters (2012b) found that the ICS was not used for all dishes, one reason being that several dishes were cooked simultaneously. There are of course many other ways that households may choose to rearrange their PIFS after the adoption of an ICS, for example let purchased biomass displace the collected biomass.

In the calculations, partly because of available emission data, the emissions of all biomass fractions are assumed identical to emissions from fuel wood combustion. Hence, the source of biomass does not alter the emissions and should a household choose to increase the share of purchased biomass at the expense of collected biomass the emission calculations would not be affected.

2.4. Calculations

The monetary savings M are calculated as the difference in money spent on fuels before and after the hypothetical introduction of the ICSs:

$$M = A_{Wood}S_3C_{Wood} + A_{Coal}S_4C_{Coal} + A_{LPG}S_5C_{LPG} - ((1-R)A_{Wood}S_{3PIF1,2}C_{Wood} + A_{Coal}S_{4PIF1,2}C_{Coal} + A_{LPG}S_{5PIF1,2}C_{LPG}) \quad (1)$$

wwhere A_X is the amount of fuel, in kg, needed for one year of cooking, C_X is the price of the fuels (note that coal and wood prices differ among the villages) per kg, R is the reduced need of fuel wood because of efficiency improvements, and S_X and S_{XPIFX} are the different fuel shares before and after the ICS adoption, respectively.

Similarly, the emission reductions in kg CO_2eq, ED, are calculated as the difference in emissions before and after ICS adoption:

$$ED = A_{Wood}(S_1+S_2+S_3)E_{Tripod} + A_{Coal}S_4E_{Coal} + A_{LPG}S_5E_{LPG} - ((1-R)A_{Wood}(S_{1PIF1,2}+S_{2PIF1,2}+S_{3PIF\ 1,2})E_{Fan,\ ICS} + A_{Coal}S_{4PIF\ 1,2}E_{Coal} + A_{LPG}S_{5PIF1,2}E_{LPG}) \quad (2)$$

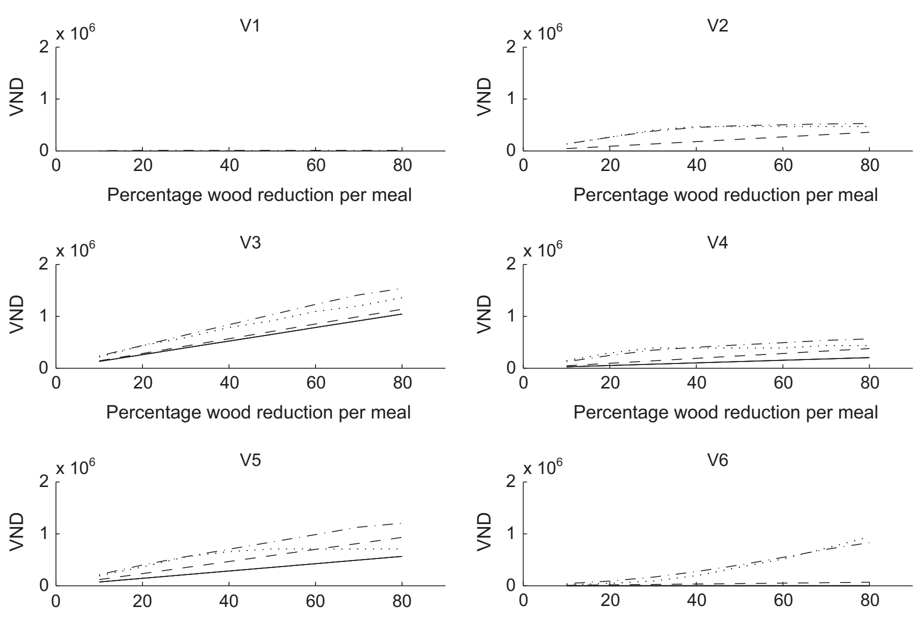

Fig. 1. Calculated annual monetary savings due to ICS adoption, M (Eq. (1)). Solid lines and dashed lines are the medians and means for assumption PIF1, respectively, and the dotted and dashed–dotted lines are the medians and means for assumption PIF2, respectively. Means and medians are presented for each village.

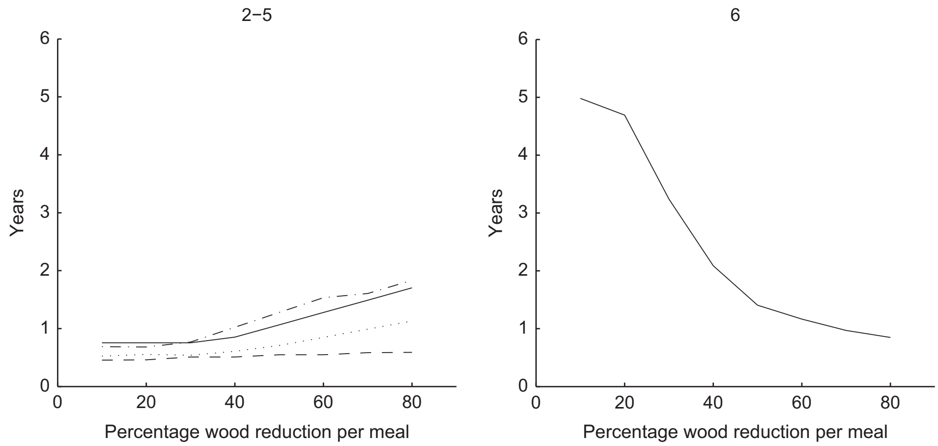

Fig. 2. Calculated median payback times for stoves in the different villages assuming PIF2. A linear correspondence between stove cost and fuel wood reduction is assumed. In the left graph, the solid line denotes V2, the dashed line V3, the dashed–dotted line V4 and the dotted line V5.

Table 3
Fuel use in different villages. The table shows the share of cooking conducted with the respective fuel on a yearly basis.

	Commune		Collected wood	Agricultural residues	Bought wood	Coal	LPG
Mountains	V1	Mean	0.95	0.046	0	0	0.01
		Std. dev.	0.103	0.100	0	0	0.035
	V2	Mean	0.62	0.15	0.18	0.02	0.04
		Std. dev.	0.308	0.193	0.205	0.076	0.150
Hills	V3	Mean	0	0.19	0.60	0.05	0.16
		Std. dev.	0	0.179	0.312	0.097	0.351
	V4	Mean	0.41	0.24	0.21	0.07	0.06
		Std. dev.	0.297	0.197	0.259	0.170	0.179
Delta	V5	Mean	0.21	0.35	0.36	0.04	0.04
		Std. dev.	0.275	0.241	0.357	0.135	0.078
	V6	Mean	0	0.23	0.03	0.33	0.41
		Std. dev.	0	0.186	0.137	0.343	0.418
	Total	Mean	0.35	0.20	0.24	0.09	0.13
		Std. dev.	0.400	0.205	0.318	0.210	0.290

where E_X, in kg CO_2eq/kg, are the emissions per kilogram of used fuels calculated per household. The results are presented as means and medians per village.

The results are presented as functions of the percentage reduction in needed fuel wood per meal (R), in Figs. 1, 2 and 4. R can be calculated as a function of cooking efficiency improvements:

$$R = 1 - \frac{\eta_1}{\eta_2} \quad (3)$$

where $\eta_{1,2}$ are the initial efficiency and the efficiency obtained after ICS adoption, respectively.

3. Results

In this section, the results of the calculations of a hypothetical stove deployment are presented. Section 3.1 presents the survey results, Section 3.2 the results of the possible monetary savings and Section 3.3 continues with the results of the emissions reduction calculations.

3.1. Survey results

The villages will henceforth be labeled V1–V6, where V1 and V2 are located in the mountainous area; V3 and V4 are located in hill area and V5 and V6 in the delta area. In all villages except V6, biomass is the dominant fuel but some households use coal and LPG to various extents, and especially in V3 several households use LPG as their main fuel. There are large differences with regard to how the biomass is obtained, whether it is collected fuel wood, bought fuel wood or agricultural residues (Table 3).

Table 4
Village means of monthly household incomes (using midpoints in categories) and land holdings.

Commune		V1	V2	V3	V4	V5	V6	Total
Income (in 10^6 VND)	Mean	1.2	1.4	2	2.3	1.7	2.9	2.0
	Std. dev.	0.44	0.82	1.06	1.22	0.68	0.85	1.05
Land holdings	Mean	9.8	6.5	3.6	7.7	5.0	3.6	6.0
	Std. dev.	4.8	3.0	1.96	3.55	2.58	1.76	3.83

In two of the villages, V3 and V6, none of the sampled households practiced fuel wood collection. While in V3 most households purchase fuel wood, in V6 it is mostly coal and LPG that is used to meet the household energy demand for cooking. The prices of the different fuels also varied between the villages, with wood being cheaper in the mountain villages at 600 VND/kg compared to 1000 VND/kg in the delta communes. The coal price varied in the opposite direction at a price of 900 VND/kg in the delta communes to 1000 VND in the mountain areas. The LPG price was constant at 21,450 VND/kg. The average monthly household income varied substantially between the villages from 1.2 million VND in the poorest mountain commune to 2.9 VND in the richest village, located in the delta area. Table 4 shows

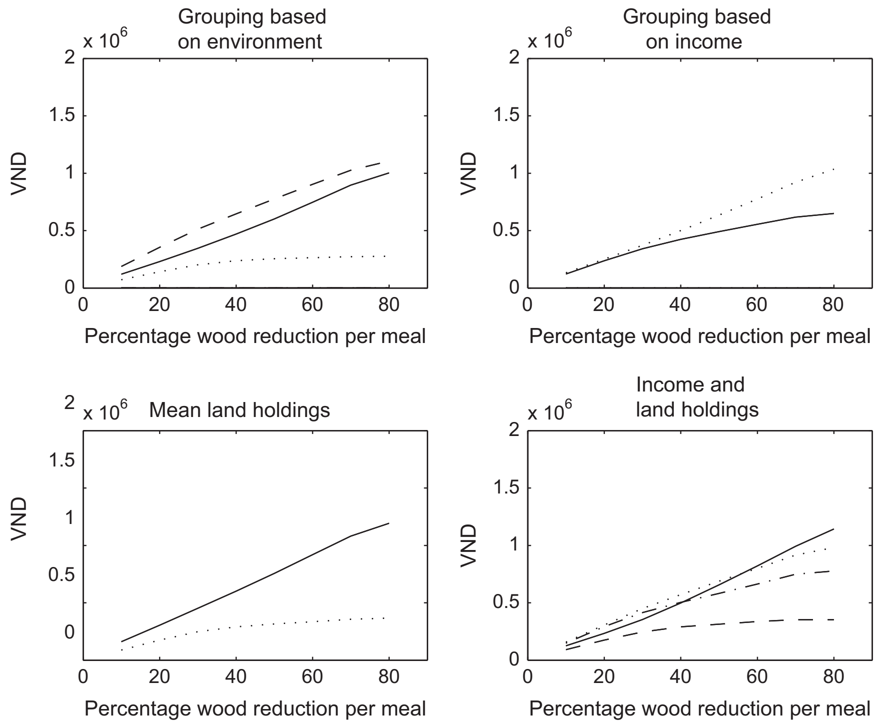

Fig. 3. Potential monetary savings, M (Eq. (1)), presented for four additional groupings: environment, income, mean land holdings, and income further divided by land holdings. Grouping based on environment: dotted line represents mountain, dashed line hills, and solid line delta. Grouping based on income: dotted line represents above average income households and solid line below average income households. Mean land holdings: dotted line represents above average mean land holdings and solid line below average income households. Grouping based on income and household land area: dotted line represents low land and low income, dashed line low income high land, solid line high income low land, and dashed dotted line high income high land.

the sample means of incomes and mean landholdings in the respective communes. Note that only one of the 240 households stated an income in the lowest income category.

3.2. Potential monetary savings

In Fig. 1, for each village, means and median values of possible yearly monetary savings, M (Eq. (1)), are presented as a function of reduction of needed wood per meal, R. Villages V2 and V4 mostly rely on collected fuels with some purchased wood in the fuel mix. In these villages, M increases with R up to a total yearly saving for $R=80\%$ of 0–0.5 MVND for V2 and 0.2–04 for V4 (median values). For assumption PIF1, the increase with R is linear while for assumption PIF2, the monetary savings increase faster for low R, up to 30–40%, and then more slowly for high R since at an R of 30–40% most commercial fuel wood has already been displaced.

For the villages with a larger share of commercial biomass fuels, V3 and V5, the monetary savings grow more strongly with R, and reach 1–1.4 MVND (V3) and 0.5–0.7 MVND (V5) at $R=80\%$ (median values). For V6, the difference between the PIF1 and PIF2 is most pronounced; for PIF1 the median values are zero for all values of R, while for PIF2 and high R, the median value is the second highest, at 0.9 MVND.

In V1, as a natural consequence of the low share of commercial fuels, the monetary savings are close to zero.

The uncertainty with regard to PIFS, which is expressed by the difference in result between PIF1 and PIF2, is for villages V2 and V4, the villages combining collected fuel wood with purchased wood, largest at an R of 30–40%, which is when most commercial fuel wood has been displaced in PIF2. For the villages that are dominated by commercial fuels, V3 and V6, the uncertainty with regard to PIFS grows with R since if PIF2 is valid, not only is the biomass utilized more efficiently but also commercial fuels are displaced to a higher degree for increasing R.

Since there is not much knowledge regarding whether the likely responses are more similar to PIF1 or PIF2, but since neither 100% PIF1 nor 100% PIF2 is very likely but rather a mix of the two, we are here assuming a scenario which is closer to PIF2 than PIF1. Then, villages V2 and V4 reach a saturation, where bought fuels are almost completely displaced by agricultural residues and collected fuel wood at $R=40\%$. The saturation levels reached under assumption PIF2 can then also be interpreted as the efficiency improvement needed before reduction in collected wood occurs for these villages. In V1, most of the fuel used for cooking is collected fuel wood; hence a linear reduction of collected fuel wood with R can be expected independent of the assumption of households behavior. However, the villages V2 and V4 and the median value for V5 display a different possible behavior. It is not until saturation is reached in terms of saved money that collected fuels start to get reduced substantially, i.e. after a reduction of 30–40% of needed fuel wood per meal, assuming that households would reduce commercial fuels before collected.

In Fig. 2, the median payback times in the different villages are plotted based on assumption PIF2 and the assumption that the stove cost is linearly increasing with R. For the villages V2–V5, the payback time increases for more expensive stoves. For village V6, however, an opposite relation is true; with increased R, a drastic reduction of the payback time is achieved. Note that a different assumption of how the cost depends on stove performance would lead to different payback times, e.g. an exponential relationship would lead to the existence of minimum points, corresponding to the lowest payback time, at an optimum R. For an exponential relationship, with the same starting and ending positions as those of the linear relationship, optimum R for V2–V5 would be at 30–40%, while for V6 it would be at 50%.

To complement the initial units of observation, the sampled communes, the households are also divided according to the local environment (mountains, hills and delta), income (high or low),

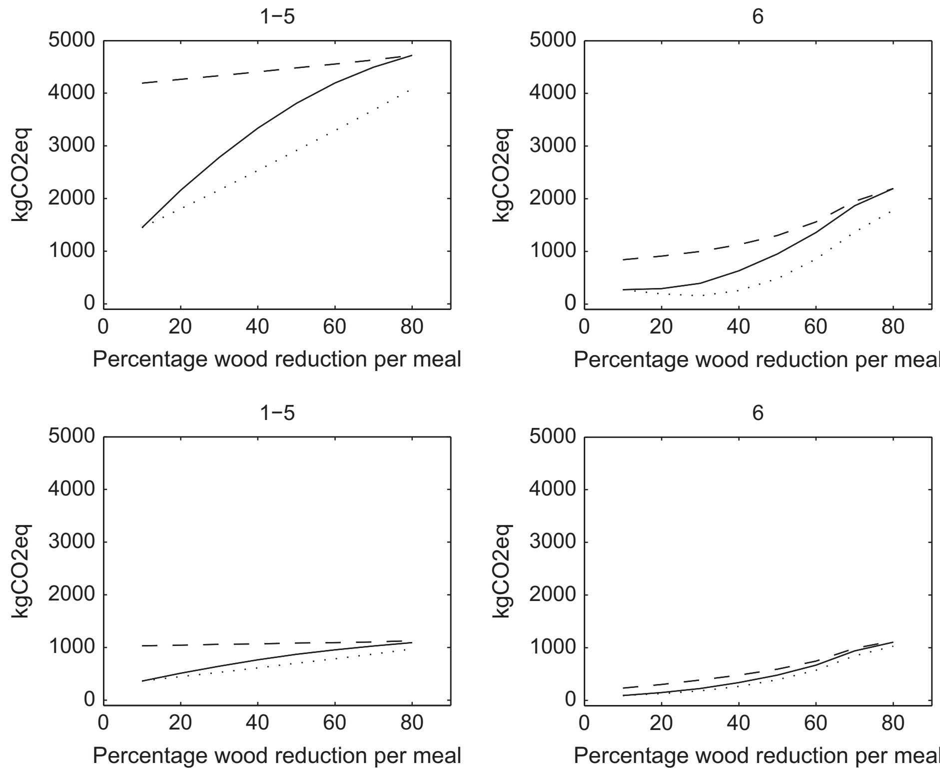

Fig. 4. Calculated CO_2eq reduction, *ED* (Eq. (2)), in villages V1–V5 (left) and village V6 (right) with all emissions (top) and only emissions included in the Kyoto Protocol (bottom). Note that the combustion of biomass is assumed CO_2 neutral. Only emissions based on assumption PIF2 are shown. Dashed line represents emissions based on fan powered gasifier stove. Dotted line represents emissions based on Chinese style ICS. Solid line represents a gradual improvement in GHG emissions as a linear function of efficiency improvement, starting from Chinese ICS and moving to fan powered gasifier stove.

household density (high or low) and a further division combining income (high or low) with households average land holdings (high or low) (Fig. 3). Note that the left column in Fig. 3 presents groupings of the studied communes into environmental areas or into three more household dense villages against the three less household dense villages, while the right column is made up of new groupings of the individual households. According to the environmental grouping, the mean savings of the households in the delta and hill areas follow each other while the mountain household's savings reach a saturation level. The difference in potential monetary savings becomes substantial at $R = 30\%$. The difference between households in more or less household dense areas is more pronounced than the difference between high and low income households. A further splitting of the high and low income households according to household land area reveals interesting patterns (Fig. 3, lower right panel). Until $R = 50\%$, the potential savings are the highest for the poor households with small land holdings while poor households with large land holdings show the lowest potential monetary savings.

3.3. Reductions in emissions of CO_2-equivalents

In this section we present the calculated reductions in emissions of CO_2-equivalents from the hypothetical stove adoption based on Eq. (2). As mentioned in Section 3.1, biomass is the dominant fuel in villages V1–V5 and consequently the emission calculation results are similar for these villages. Thus, only results for these villages combined, treated as one region in the calculations, are presented and compared with the results for the fossil fuel dominated V6. Furthermore, PIF1 and PIF2 generate similar results for villages V1–V5, whereas in village V6, the reduction achieved assuming PIF1 is close to zero, because of the low initial usage of biomass. We thus show the results only for assumption PIF2.

In Fig. 4, the calculated CO_2eq reductions are shown as a function of *R* for the two different stove types of the biomass dominated villages (left column) and fossil fuel dominated village (right column). Note that these curves do not pass through the origin because they show not only a reduction of CO_2-equivalents as a function of lower usage of fuel wood, but also a decrease per kg fuel wood due to different stove technologies. The upper graphs show the CO_2eq reductions for all climate agents while the lower graphs show the result when only greenhouse gases included in the Kyoto protocol are included in the calculations. For the biomass dominated villages, V1–V5, if emissions of CO_2-equivalents are comparable, on a per unit biomass level, to those of the gasifier stove, further reductions through a higher *R* are of less importance. This is due to the following reasons: the gasifier stove reduces the emissions of black carbon and methane; the GHG emissions per used fuel wood are low if the biomass is assumed carbon neutral and the *R* level is naturally of higher importance for a stove with higher GHG emissions per kg of used biomass.

For village V6 and assumption PIF2, a more efficient cook stove displaces more fossil fuels and hence the stove efficiency has a high impact on the emission calculations for both of the assumed emission levels per kg fuel wood. At $R = 30\%$, there is a dip in GWP reductions for the case of the Chinese ICS since according to PIF2, households switch from LPG to wood when this becomes economical. Thus, the *R* value of this dip depends on a combination of wood and LPG prices.

The households of V6 utilize a large share of LPG for their cooking, which partly explains why V6 would achieve relatively low emission reductions, even when fossil fuels are displaced, compared to the villages where biomass is the major cooking fuel. However, if only emissions viable for carbon credits, methane and CO_2 are included (from fossil sources), V6 achieves comparable

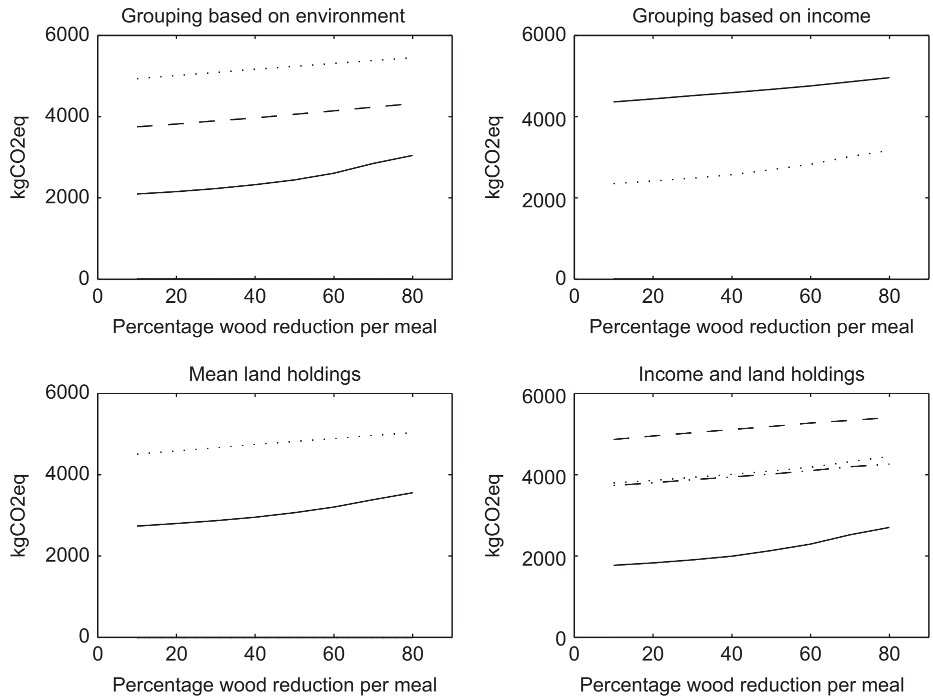

Fig. 5. Mean potential emission reductions *ED* of Eq. (2), in kg CO_2eq for additional groupings. The emissions include black carbon and are calculated for scenario PIF2 using the gasifier stove emissions. Grouping based on environment: dotted line represents mountains, dashed line hills, and solid line delta. Grouping based on income: dotted line represents above average income households and solid line below average income households. Mean land holdings: dotted line represents above average mean land holdings and solid line below average income households. Grouping based on income and household land area: dotted line represents low land and low income, dashed line low income high land, solid line high income low land, and dashed dotted line high income high land.

emissions compared to the other villages' reductions, for high *R* values (see Fig. 4 bottom row).

Fig. 5 shows the potential reductions in emissions, *ED* of Eq. (2), for the same groupings as in Fig. 3, for the gasifier stove and PIF2. A comparison of Figs. 5 and 3 reveals that in general the households with the highest potential monetary savings from increasing *R* are the households showing the smallest potential CO_2eq reductions with the only exception of poor households with small land holdings which score high in both aspects.

4. Discussion

Several studies have described multiple fuel (fuel stacking) strategies of rural households (Heltberg, 2005; Masera et al., 2000; Peng et al., 2010). This paper found strong local patterns in fuel mixes on village level, Section 3.1, and possible consequences of these local variations in fuel mixes for ICS programs have been examined.

In densely populated agricultural areas in Vietnam (Tuan and Lefevre, 1996) and China (Kaul and Liu, 1992), the fuel combination of agricultural residues and coal is common, where coal is used when residues are not available. In V6, a combination of LPG, coal and agricultural residues constitutes the main part of the fuel mix, and this may actually be an area suitable for ICS dissemination provided ICSs with sufficiently high conversion efficiency are used and that the assumption that biomass will displace fossil fuels when it is economic is valid. For a high share of the households, there are substantial possible monetary savings by the use of an ICS and income levels are on average higher, which may facilitate stove purchases and stove repairs. For Kyoto protocol GHGs, V6 achieves a high level of emission reductions compared to the other villages. This indicates the possibility of carbon credits as partial financing for stove programs in areas where a high percentage of the households also have monetary incentives for an efficient stove use.

Furthermore, from a climate perspective, considering the high monetary savings possible to be obtained in V6 (Fig. 1) and the large potential emission reductions of CO_2eq (Fig. 4), the potential CO_2eq reductions in V6 may be larger than those in the villages relying on collected biomass assuming that ICS adoption and usage depend both on the possible monetary savings and the means for stove purchase and repairs. This is especially true if only the greenhouse agents currently included in the Kyoto protocol and for high stove efficiencies are considered. Research related to stove adoption and sustained usage based on initial fuel mixes and incomes would thus be useful in order to properly evaluate the combined health and climate benefits.

However, there are also poor areas with potential substantial possible monetary savings for several households. The village means of monthly incomes vary from 1.2 to 2.9 million VND (Table 4). One of the poorer communes V5, has one of the highest possible monetary savings from ICS deployment for both PIFS assumptions and for the entire range of stove efficiencies. Also in the hill region, the possible total savings are larger for the poorer village, V3, than for V4 for both PIFS. Hence, monetary savings depend not solely on income but may vary between areas due to other factors. This is further underlined by an examination of Fig. 3, which shows that for poor households with small land holdings the potential monetary savings are on par with or higher than those for relatively richer households. While all the households sampled in this study report an income, for many households in developing countries, possible monetary savings are not an issue since they do not partake in the monetary economy (Pachauri and Spreng, 2012).

The positive effect of reducing fuel wood collection time is often pointed out as an important motivation for improved stove programs. However, since many households complement their collected fuels with purchased fuels, the time spent on gathering fuel wood may not be reduced until a high ICS efficiency is achieved (although an ICS may still reduce the time used for cooking). It can be argued that the welfare effect is greater when the usage of a purchased fuel is reduced rather than collected fuel due to the reason that if the household would value the time more than the money, it would not collect in the first place. However, since the household members responsible for collection of fuel and cooking may not be the ones deciding which fuels to use, this need not be true for all individual members or for the household in total (Miller and Mobarak, 2013). Policies with the aim of improving the situation especially for the fuel wood collecting members of the household may need to consider this. In villages where both collected and bought fuels are utilized, households or persons within households making decisions may not receive incentives for purchasing the most efficient stoves since a further improvement in efficiency may not lead to further monetary savings (Fig. 1). Households have been found to be more willing to make purchases that save money rather than save time (Arnold et al., 2006; Shepherd, 1990).

One of the underlying assumptions for the potential money savings is lack of possibilities to sell excess collected fuel wood and agricultural residues; the data used in this article do not contain information about how many of the households are selling fuel wood. The establishment of a market for local biomass might give incentives for either the adoption of ICS or fuel switching through providing a direct monetary value of the biomass.

The results in Figs. 1 and 3 may also have implications for the type of stoves that ought to be chosen by an intervention program. In V6, stove efficiency is more important than the GHG emissions per unit biomass (Table 1) in order to achieve emission reductions (both for total GHG emissions and for Kyoto protocol GHGs). For the biomass dominated villages, on the other hand, the reduction in GHG emissions per kg biomass appears to be more important than energy efficiency in order to achieve overall GHG emission reductions. The findings regarding stove suitability with regard to GHG emissions also, to some extent, correspond to the stove types found to be most attractive to the households in terms of economy; again in V6 high stove efficiencies are needed while in the biomass dominated villages, high efficiencies may not improve the attractiveness of an ICS (see Fig. 2).

Alignment of climate policies with development goals is probably a key to the successful involvement of developing nations in binding climate agreements. A further inspection of Fig. 3 clearly indicates that without the consideration of black carbon the climate benefits of improved stove will likely be underestimated, both in terms of size and distribution. In the poorer, biomass relying villages, an inclusion of black carbon in a future climate agreement could provide incentives for ICS adoption through carbon financing in a post-Kyoto CDM (Clean Development Mechanism) mechanism or similar one. It should however be noted that the radiative forcing for both black and organic carbon is still uncertain and furthermore may vary between regions (Bond et al., 2013). Furthermore the calculation rests on laboratory measurements for the considered cooking options; the differences in emissions between traditional cooking and cooking with an ICS need further in household measurements.

One recent randomized trial with freely subsidized cook stoves achieved an almost 100% adoption, a 30% reduction of used fuel wood and a significant decrease in health indicators linked to indoor air pollution (Bensch and Peters, 2012b). While it is not entirely clear what separates the study by Bensch and Peters (2012b) from the study by Hanna et al. (2012) with much more discouraging results, Bensch and Peters (2012b) showed that the right stove disseminated in the right place may indeed be a recipe for success. Some of the differences that can be identified are intervention area and stove technology. Linking the adoption and usage in studies such as Bensch and Peters (2012b) and Hanna et al. (2012) with household and area data together with different stove options could give valuable insight into which degree different stoves would perform under different circumstances.

Improved biomass stoves as a possible cost efficient mitigation strategy have been previously pointed out (Grieshop et al., 2011; Panwar, 2009; Panwar et al., 2009). It is also clear from inspection of the results from the emissions calculations in Fig. 4 that this paper also supports this conclusion for a range of assumptions on stove costs and lifetimes and could be financed through for example a future CDM like scheme. However this depends on the assumptions concerning the original emission levels together with assumptions that the stoves are used in a way that achieves sufficient reductions and that this usage is sustained during the assumed program lifetime. The very different results that recent programs have experienced make such estimations difficult (Bensch and Peters, 2012b; Hanna et al., 2012). On the other hand a cleverly implemented program may spark a sustained usage beyond the program should the households find that the stoves are a cost effective way to enhance their welfare through direct monetary savings, increased health or reduced need for fuel wood collection. Furthermore, the relatively large differences for the results on the two assumptions of how an ICS may influence households' fuel stacks (PIFS) point towards a need for better understanding of how improved stoves may affect fuel choices in order to properly evaluate how these stoves would perform in areas where multiple fuel use is common.

It should also be pointed out that including the possible health benefits from an improved stove program has large impacts on any cost–benefit evaluation (Smith and Haigler, 2008). Targeting solid fuel use in developing countries thus provides opportunities for both improving the health situation as well as reducing climate warming emissions (Kumar and Viswanathan, 2011). However, how health improvements are mapped from a reduction in indoor air pollution is still uncertain in the ranges attained for cooking with solid fuels; Smith and Peel (2010) found a possible logarithmic dependence from exposure to risk for certain diseases. This strengthens the case for stove options that reach high levels of local emission reductions such as the gasifier stove or fuel switching to LPG (Grieshop et al., 2011). Furthermore, this may have implications for households that keep cooking with any solid fuel outside the ICS, for example a household that will still be dependent on coal to some extent; hence a good understanding of households' fuel stacks before and after intervention is also needed for estimating health benefits.

The results presented in this paper are based on a case study of six villages and depend on assumptions concerning stove performances and usage together with households' post-ICS-adoption fuel stacks (PIFS). Most of the results are likely to be generally valid for areas with similar conditions to the one where this study was carried out but there are also important local variations that should be considered before general conclusions can be drawn. This article points towards large uncertainties for any cost benefit calculation, depending on initial and post-adoption fuel use, but also on possibilities in using knowledge of area dependent fuel mixes in order to make an initial effort of stove dissemination successful. In order to further improve the policy value of the results, empirical studies of stove use as a function of initial fuel mixes in combination with statistical models of fuel use could result in more accurate estimations of the potential benefits of a large scale stove dissemination program.

5. Conclusions

In this paper, based on data of household multiple fuel usage from six villages in northern Vietnam, possible outcomes in terms of monetary savings and greenhouse gas emission reductions of ICS deployment have been calculated for various assumptions of stove performance and households post-ICS-adoption fuel stacks.

Using actual household data it has been shown that the relationship between stove performance and some of the possible benefits in many cases is non-linear. The effects of ICS deployment, which depend on the actual reduction of required biomass for cooking, differ substantially among the villages in terms of monetary savings and emission reductions.

Although villages dependent on a large share of purchased biomass are most suitable for stove dissemination (under most assumptions), villages to a large extent relying on fossil fuels may also be potential candidates for ICSs, if biomass displaces fossil fuel because of a more efficient utilization and sufficient stove quality.

In fossil fuel dominated areas, high efficiency ICSs are needed both for making them financially attractive for households and for making any substantial difference in terms of emission reductions. In areas where a high share of the fuel is collected biomass, households' monetary savings are not increased after certain levels of reduced need for fuel wood are achieved and the global warming contributing to emissions of CO_2-equivalents per unit used biomass is more important than the overall stove efficiency.

One of the aims of many improved cook stove programs is to reduce the time spent on wood collection, often with a focus on improving women's livelihoods. However, this study shows that for many households in several villages, fuel wood collection might not be reduced until a substantial stove efficiency improvement is achieved.

Since black carbon is not included in the Kyoto protocol, and potential black carbon emission reduction is an important benefit of ICS adoption but the reductions vary strongly both with ICS types and the villages, there is a considerable risk that current carbon financing of ICS will lead to suboptimal GHG emission reductions.

Finally, this article has showed that there are considerable differences in the prospects for ICS adoption among relatively nearby villages within the same province. Potential ICS programs may benefit by carefully choosing program villages and areas with potential monetary savings from ICS deployment and, further, tailor the stove programs for the different needs of the respective areas. Furthermore, this does not necessarily interfere with an aim of poverty reduction, since poor households with small landholdings are often the main beneficiaries.

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